AFRL-VS-HA-TR-98-0120 NWRA-CR-98-R186

Investigations of the Effects of Ionospheric Total Electron Content and Scintillation on Transionospheric Radio Wave Propagation

C.C. Andreasen
E.J. Fremouw
E.A. Holland
A.J. Mazzella, Jr.
G.-S Rao
J.A. Secan

NorthWest Research Associates, Inc.
P.O. Box 3027
Bellevue, WA 98009-3027

26 October 1998

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
29 Randolph Rd
AIR FORCE MATERIEL COMMAND
Hanscom AFB, MA 01731-3010

20020603 138

This Technical Report has been reviewed and is approved for publication.

Gregory Bishop
Contract Manager

Odile de La Beaujardière, Chief
Space Plasma Disturbance Specification and Forecast Team

This report has been reviewed by the ESC Public Affairs Office (PA) and is releasable to the National Technical Information Service.

Qualified requestors may obtain additional copies from the Defense Technical Information Center (DTIC). All others should apply to the National Technical Information Service (NTIS).

If your address has changed, if you wish to be removed from the mailing list, of if the address is no longer employed by your organization, please notify AFRL/VSIM, 29 Randolph Rd., Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or another aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	19 October 1998	Final 8 July 1994 - 31 August 1998

4. TITLE AND SUBTITLE
Investigations of Ionospheric Total Electron Content and Scintillation Effects on Transionospheric Radiowave Propagation

5. FUNDING NUMBERS
F19628-94-C-0067
PE 62601F
PR DMSP
TA GH
WU AA

6. AUTHOR(S)
C. Charley Andreasen, Edward J. Fremouw, Elizabeth A. Holland, Andrew J. Mazzella Jr., Guan-Shu Rao, James A. Secan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Northwest Research Associates, Inc.
14508 NE 20th Street
P.O. Box 3027
Bellevue, WA 98009-3027

8. PERFORMING ORGANIZATION REPORT NUMBER
NWRA-CR-98-R186

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010
Contract Manager: Greg Bishop / VSBP

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
AFRL-VS-HA-TR-98-0120

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release - distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Numerous DoD communication, navigation, and surveillance systems depend upon transionospheric propagation of radio signals between space and the ground. The group delay and phase advance encountered by such signals depend upon the path integral of ionospheric plasma density – the so-called total electron content (TEC). Their phase and intensity also can fluctuate due to refractive/diffractive scatter in plasma-density irregularities – i.e., they can suffer complex-signal scintillation. In this project, Northwest Research Associates (NWRA) collaborated with researchers at the Air Force Research Laboratory (AFRL) at Hanscom AFB in the observation and modeling of TEC and scintillation. Central to the TEC effort was operation and refinement of the Air Force Ionospheric Measuring System (AN/GMQ-35). The scintillation effort was confined to development of operational code, called WBMGRID, for running a gridded version of NWRA's scintillation model, WBMOD, with AFRL's Scintillation Decision Aid (SCINDA). Late in the project, effort was re-directed from scintillation research to broader ionospheric questions, as part of the High Frequency Active Auroral Research Program.

14. SUBJECT TERMS
Global Positioning System (GPS), High Frequency Active Auroral Research Program (HAARP), Ionosphere, Radiowave scintillation, Space weather, Total electron content (TEC)

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OFABSTRACT
Unclassified	Unclassified	Unclassified	SAR

Contents

Figures

Tables

Preface

This report summarizes the work completed during a project focused on studies of the effects of the earth's ionosphere on transionospheric radiowave propagation.

We express our appreciation to TSgt. Carlton Curtis of the Air Force Research Laboratory (AFRL) at Hanscom AFB for his collaboration in many of the investigations and support efforts for the Ionospheric Measuring System and other projects for measuring ionospheric total electron content and scintillation.

Several organizational changes occurred during the term of this contract, with both the Albuquerque and Hanscom sites of Phillips Laboratory becoming part of AFRL, and 50th Weather Squadron becoming 55th Space Weather Squadron. For simplicity, these organizations are referenced by their latest designations, although the reference may not be chronologically correct.

List of Abbreviations and Acronyms

55 SWXS	55th Space Weather Squadron
AFRL	Air Force Research Laboratory
APTI	Advanced Power Technology, Inc.
AWN	Automated Weather Network
CSDL	Charles Stark Draper Laboratory
DCP	Differential Carrier Phase
DGD	Differential Group Delay
GPS	Global Positioning System
HAARP	High-frequency Active Auroral Research Program
IMS	Ionospheric Measuring System
IPP	Ionospheric Penetration Point
NIMS	Navy Ionospheric Measuring System
NNSS	Navy Navigation Satellite System
NWRA	NorthWest Research Associates
PLH	Phillips Laboratory at Hanscom
RTM	Real-Time Monitor
SCINDA	Scintillation Decision Aid
SFG	Scale Factor Generator
TEC	Total Electron Content
TELSI	TEC and Scintillation (message format)

Investigations of Ionospheric Total Electron Content and Scintillation Effects on Transionospheric Radiowave Propagation

1. Introduction

The overall objective of this project was to improve our understanding of ionospheric effects on transionospheric radiowave propagation. The phenomena studied cover the full range of scale sizes from tens of meters to thousands of kilometers. The twelve tasks outlined in the proposal for this work [Fremouw *et al*, 1994] can be grouped into the following six study areas. (The tasks in the proposal corresponding to these study areas are indicated in parentheses.)

1. Investigate the logarithmic slope of the phase-scintillation power-density spectrum (PDS) at large scales in the equatorial region. Develop a model for a two-regime power-law PDS based on results of the investigation and implement it in the WBMOD ionospheric scintillation model. (Tasks 1 and 2)

2. Investigate the magnitude and behavior of small-scale phase gradients, using the equatorial scintillation data sets built in the first study. Develop algorithms for including the effects of small-scale phase gradients on transionospheric propagation and implement them in WBMOD. (Tasks 3 and 4)

3. Develop models consistent with the current propagation algorithm in WBMOD for individual intermediate-scale ionospheric features associated with enhanced scintillation (equatorial plumes, polar patches, auroral boundary blobs), and implement them in WBMOD. (Tasks 5 and 6)

4. Develop techniques for producing short-term forecasts of scintillation over large areas, implementing and demonstrating these techniques in computer programs. (Task 7)

5. Deploy, operate, and maintain satellite receiver instrumentation on a long-term basis at local and remote sites to collect databases of ionospheric total electron content (TEC) and scintillation. Use these data to (a) analyze performance of ionospheric monitors, (b) validate models of ionospheric behavior, and (c) develop and formulate algorithms to improve the performance of both ionospheric monitors and models. (Tasks 8 and 10)

6. Deploy, operate, and maintain satellite receivers on a short-term basis at local and remote sites where unique opportunities exist for enhancement of test data sets, particularly where other instruments have been deployed to perform complementary ionospheric measurements. Collect these data, and ancillary data from other instrumentation, into documented data sets that can be used as outlined in the previous study description. (Tasks 8, 9, and 12)

In response to a memorandum from the Contracting Officer dated 6 June 1996, Northwest Research Associates (NWRA) shifted emphasis from study areas 1 through 4, above, to study areas 5 and 6. As regards study area 6, especially, NWRA participated in the High-frequency Active Auroral Research Program (HAARP), managed by the Air Force Research Laboratory (AFRL) and the Office of Naval Research (ONR). HAARP activities are reported in Section 6.

2. Equatorial Phase Scintillation

2.1 Two-regime Spectral Characterization

In the equatorial region, the WBMOD ionospheric scintillation model describes the phase-scintillation power-density spectrum (PDS) as a single power law with a slope [on a plot of log(power) vs. log(frequency)] of -2.5. The choice of a single-regime spectrum and the specified slope both were based on analysis of VHF scintillation data collected at Ancon, Peru, and Kwajalein Island during the Wideband beacon satellite experiment, which focused on the fluctuation-frequency range of 0.5 to 10.0 Hz. Anecdotal evidence in the form of phase spectra collected from another system also operating through the equatorial ionosphere at frequencies above L band [Brown, private correspondence] showed slopes of the phase PDS in the range -3.5 to -4.0 over a range of spatial scales corresponding to frequencies below the 0.5-Hz cutoff employed in the Wideband analysis. The first aspect of this task was to revisit a subset of the Wideband equatorial data to look for evidence of a steepening in the phase spectrum at lower frequencies. Assuming such evidence would be found, the second aspect was to develop a two-regime description of the PDS of the plasma-density irregularities that cause scintillation that could be implemented in WBMOD. We summarize the results of those studies here; details can be found in Section 3 of Scientific Report #1 (SR1) for this contract [Secan *et al.*, 1995].

Data tapes containing raw in-phase (I) and quadrature (Q) pairs from 49 Wideband passes taken at Ancon (21) and Kwajalein (28) during the years 1977 and 1979 were provided by Dr. Dennis Knepp of Mission Research Corporation. We processed the L-band and VHF data from all 49 passes using a more robust set of procedures than was used in the original Wideband processing, as described in Section 3.1 of SR1. The following parameters were generated from the analysis of this set of approximately 500 spectra (250 L-band, 250 VHF):

p_l : The (negative) slope of the phase PDS over the fluctuation-frequency range 0.01 to 0.1 Hz, obtained from a linear fit in log(power) vs. log(frequency);

T_l : The PSD (in dB relative to 1 rad^2/Hz) at log(f) = -1.5, from the 0.01 to 0.1-Hz linear fit;

p_h : The (negative) slope of the phase PDS over the frequency range 0.1 to 1.0 Hz, obtained from a linear fit in log(power) vs. log(frequency);

T_h : The PSD (in dB) at log(f) = 0.5, from the 0.1 to 1.0-Hz linear fit;

f_b : The frequency where the PDS "breaks" from a steep low-frequency regime to a shallower high-frequency regime, derived from a simple analysis of slopes of sub-samples of the spectrum.

The rationale for how these parameters are defined and how they were obtained from the spectra is given in detail in SR1.

The primary finding of the data analysis was that there is indeed strong evidence in this set of spectra for a low-frequency steepening of the phase PDS, with a high-frequency slope (p_h) of ~ 3.0, a low-frequency slope (p_l) of ~ 4.0, and a break frequency (f_b) of ~ 0.11 Hz (corresponding to an *in situ* scale-size of ~5.5 km) based on analysis of the L-band spectra. The high- and low-frequency slopes derived from the VHF data were ~ 2.3 and 3.9, respectively. We attribute the difference in the slope of the high-frequency sections of the L band and VHF spectra to diffraction effects on the VHF phase, which will drive the spectrum to shallower slopes than would be generated by purely refractive scatter. This appears to reconcile the differences noted between the slopes generated from the WBMOD model, which had been derived from analysis of Wideband VHF data, and those found in the Brown data set. If the Wideband L-band data are processed to focus on larger spatial scales (lower fluctuation frequencies), the spectra do tend to a steeper slope than is seen at higher fluctuation frequencies.

The next stage in this task was to develop a formalism for implementing a two-regime model for the ionospheric irregularities that cause scintillation in the WBMOD propagation model. The model separates the spectrum into two power-law components that are summed together to generate the total spectrum. For the temporal phase spectrum, $P_\varphi(f)$, the resulting forms of the two components of the spectrum are

$$P_l(f) = T_l \frac{\left(f_o^2 + f_l^2\right)^{pl/2}}{\left(f_o^2 + f^2\right)^{pl/2}}, \text{ and} \tag{1}$$

$$P_h(f) = T_h \frac{\left(f_o^2 + f_h^2\right)^{ph/2}}{\left(f_o^2 + f^2\right)^{ph/2}}, \tag{2}$$

where T_l is defined at f_l = 1/60 Hz and T_h is defined at f_h = 1 Hz. The total spectrum at a given frequency is then the sum of the two components at that frequency.

A simple algorithm for fitting the phase spectrum defined by Eqs. (1) and (2) was developed to demonstrate how the model parameters required (p_l, T_l, p_h, and T_h) could be extracted from an observed phase PDS. The algorithm starts with estimates for these parameters derived from the two linear least-squares fits to log(power) vs. log(f), described above, and then uses a non-linear least-squares fitting technique to refine the estimates. Figure 1 illustrates the results of such a fit to an L band phase PDS calculated from data taken at Kwajalein Island.

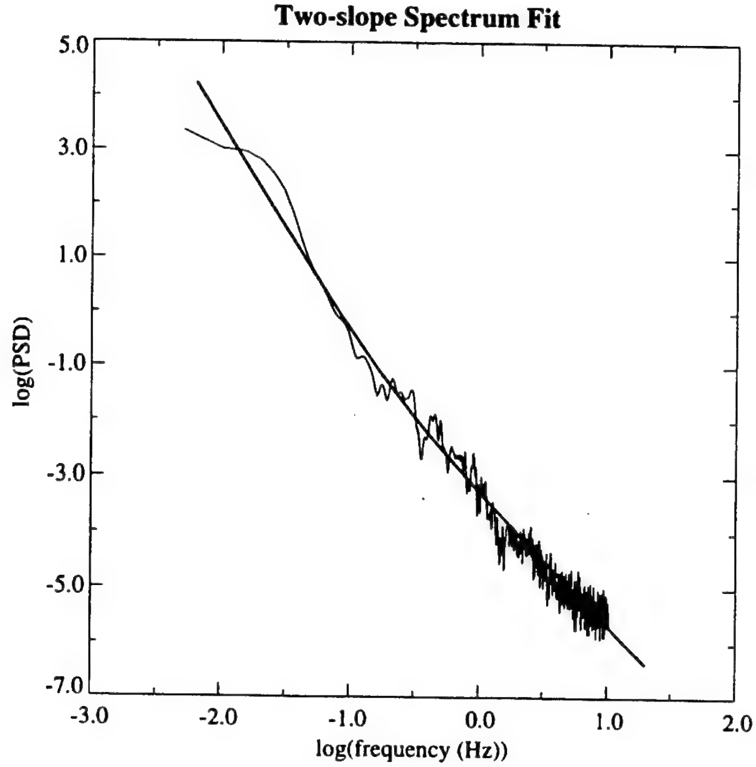

Fig. 1. Example of the results of fitting the two-regime temporal-phase PDS model (heavy solid curve) to an observed L-band phase PDS (light solid curve).

2.2 Real-Time Analysis and Prediction

The objective of this task was to develop techniques for using nearly real-time observations of ionospheric plasma-density irregularities to update the WBMOD climatology and to implement them in software to be used by the USAF 55th Space Weather Squadron (SWXS), located at Schriever AFB, CO. The primary data sources to be used were *in-situ* observations of plasma-density irregularities from the Defense Meteorological Satellite Program (DMSP) Special Sensor for Ions, Electrons, and Scintillation (SSIES) and intensity-scintillation observations from AFRL-deployed receivers in the South American region. Three subtasks were completed: development of algorithms and software for calculating estimates of the height-integrated irregularity strength, C_kL, from the observed intensity-scintillation indices, S_4; development of algorithms for using SSIES and ground-based observations of C_kL to update the equatorial section of the WBMOD model; and implementation of these algorithms in software to be part of the AFRL Scintillation Decision Aid (SCINDA) system. We summarize the results of each of these subtasks here; details may be found in Section 3 of Scientific Report No. 2 (SR2) for this contract [Andreasen *et al.*, 1996].

The algorithms for calculating C_kL from observed S_4 values were taken from software developed on an earlier project (program GBCKL), which calculated estimates of C_kL from both

intensity and phase scintillation observations from GPS receivers [Secan *et al.*, 1990]. These algorithms were tailored for the current purpose and implemented in the S4CKL code, which was delivered to AFRL for implementation as part of the SCINDA system.

Techniques were developed for using two sources of nearly real-time observations of ionospheric irregularities to update the model of these irregularities in WBMOD: estimates of the probability that Raleigh-Taylor instabilities will grow in the post-sunset ionospheric F-region from an analysis of plasma density measured *in situ* by means of DMSP SSIES; and observations of S_4 from three stations in Latin American (Ancon, Peru; Antofagasta, Chile; and Howard AFB, Panama). The analysis of the DMSP SSIES data is to be provided by means of algorithms developed by P. Sultan of AFRL [Sultan, 1996]. These direct measures of scintillation supplement the surrogate measures of solar and geophysical conditions normally used to drive the environment models in WBMOD (sunspot number, geomagnetic index, season, *etc.*). The following general guidelines were developed for using these various input data:

1. If neither SSIES analyses nor S_4 measurements are available, the standard WBMOD climatological models for the distribution of irregularities in the equatorial region are used, driven by the best-available estimates for the various solar-geophysical indices required by the climatology model.

2. If only an SSIES analysis is available and it is determined to be valid for use at the time and location for which the model is running (see Section 3.3.1 of SR2 for a discussion of how this validity was determined), it is used to set the position in the WBMOD climatological distribution of C_kL to either the plume or non-plume population, depending on whether the SSIES analysis value is above or below 0.5, respectively. All spatial and temporal variations of the irregularity distributions are derived using the underlying WBMOD climatology.

3. If C_kL values are available (from the S_4 observations), they are used to adjust the latitudinal variation of C_kL for all regions outside the latitude/longitude area within which the SCINDA system will be placing plume structures. Inside the SCINDA-analysis region, C_kL will be set to a non-plume value, either one explicitly input to the analysis or one derived from the non-plume WBMOD climatology. The latitude variation of C_kL derived from this analysis is also provided to the SCINDA system for use in specifying the latitude variation of C_kL within plume structures. Details of the adjustment process are presented in Section 3.3.2 of SR2.

The final subtask was to develop a software-based system for generating spatial latitude-by-longitude grids of intensity scintillation (the S_4 index) computed by means of the real-time update algorithms. A set of four computer programs was developed, known collectively as the WBMGRID system. Figure 2 shows the flow of control and data through this system, as delivered to AFRL for incorporation in SCINDA. The four programs have a simplified user interface, which reads inputs from a single ASCII-format file that can be constructed either manually via a text editor or automatically by a more sophisticated graphical user interface. Functionally, the WBMGRID programs (1) define a grid of geographic locations that will form one end of a set of ground-to-geostationary-orbit ray paths (program LLGRID), (2) calculate

various geometry-related parameters used in the scintillation calculations along each ray path (program GEOMGRID), (3) calculate eight ionospheric plasma-density-irregularity parameters for each ray path based on the WBMOD climatology updated with real-time observations (program IRRGRID), and (4) calculate S_4 along each ray path (program S4GRID).

Aside from software design considerations, the functions performed by the WBMGRID suite were divided among several programs for three reasons: (1) to make definition of the grid on which the calculations are made independent of all other calculations (program LLGRID), (2) to isolate CPU-intensive calculations that need be performed only once for a given scenario (program GEOMGRID), and (3) to separate generation of the ionosphere (program IRRGRID) from the propagation calculations (program S4GRID) to permit other programs to alter the ionospheric parameters (primarily C_kL) based on analysis of data not available to or usable by program IRRGRID. A User's Manual was written for the WBMGRID codes and was included as Appendix B in SR2. Details such as input data and file formats are provided there.

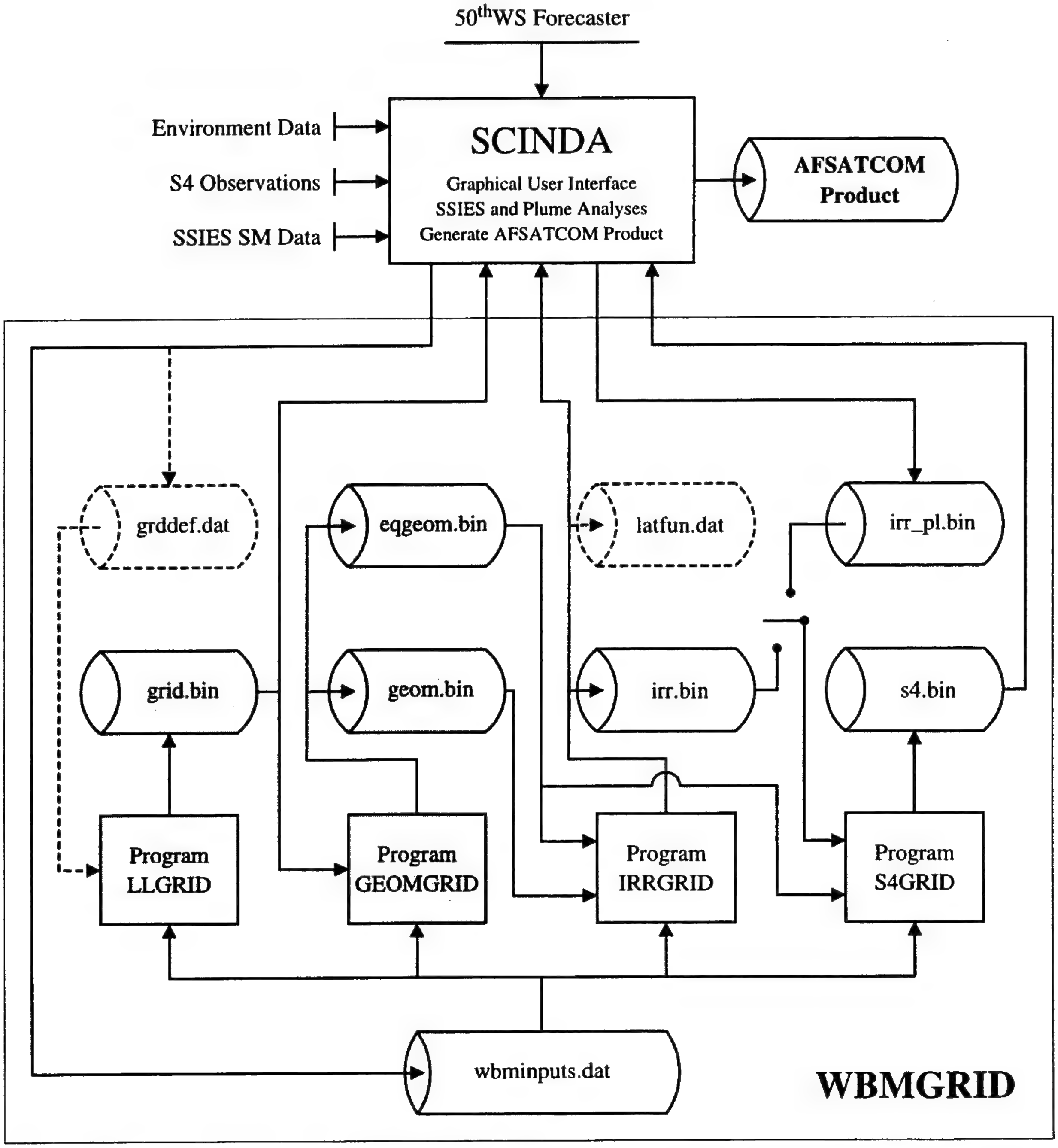

Fig. 2. Flow diagram of the WBMGRID software in a sample implementation as part of the SCINDA system. Shaded programs and output files need be run only if the scenario geometry changes (such as different output grid, different satellite location, etc.). Dashed items are optional.

3. Ionospheric Measurements

3.1 IMS Developments

The Ionospheric Measuring System (IMS) is a semi-autonomous system that utilizes the Global Positioning System (GPS) to perform TEC measurements along the lines of sight to GPS satellites. NWRA supported installation of the IMS units at field sites at Otis Air National Guard Base, Massachusetts in October 1994; Croughton Royal Air Force Base, United Kingdom in March 1995; Thule Air Base, Greenland in August 1995; and Eareckson Air Force Station, Shemya, Alaska in September 1996. NWRA also supported installation of the fifth IMS unit at the Charles Stark Draper Laboratory (CSDL) when that system was returned to its developer from the Sacramento Air Logistics Center (SM-ALC) in February 1996, and re-installed this system at Hanscom Air Force Base in March 1997 when it was re-delivered by CSDL. Concurrent efforts have supported regular operations of the IMS and development of the data collection, archiving, and analysis for it.

A diagram of the IMS in its current configuration is displayed in Figure 3. Each of the original IMS units consisted of an Ashtech Z-12 dual-frequency GPS receiver, a Micropulse antenna in a custom-built housing, two Hewlett-Packard UNIX processors operating in an alternating mode, an external common disk for the two processors, two tape drives, a Netblazer communications processor, six modems (two for Automated Weather Network (AWN) communications and four for interactive dialup communications), a custom-built "heartbeat" power controller, and an uninterruptable power supply (UPS). During the initial deployment at Otis, and for all subsequent deployments, the IMS unit was supplemented with a personal computer ("Companion PC") having a network connection to the IMS. The Companion PC was configured initially to handle tape archiving of the IMS data, circumventing difficulties with the original tape-archiving process, and to expedite dialup communications, but its role gradually has been augmented to perform essential functions for the IMS.

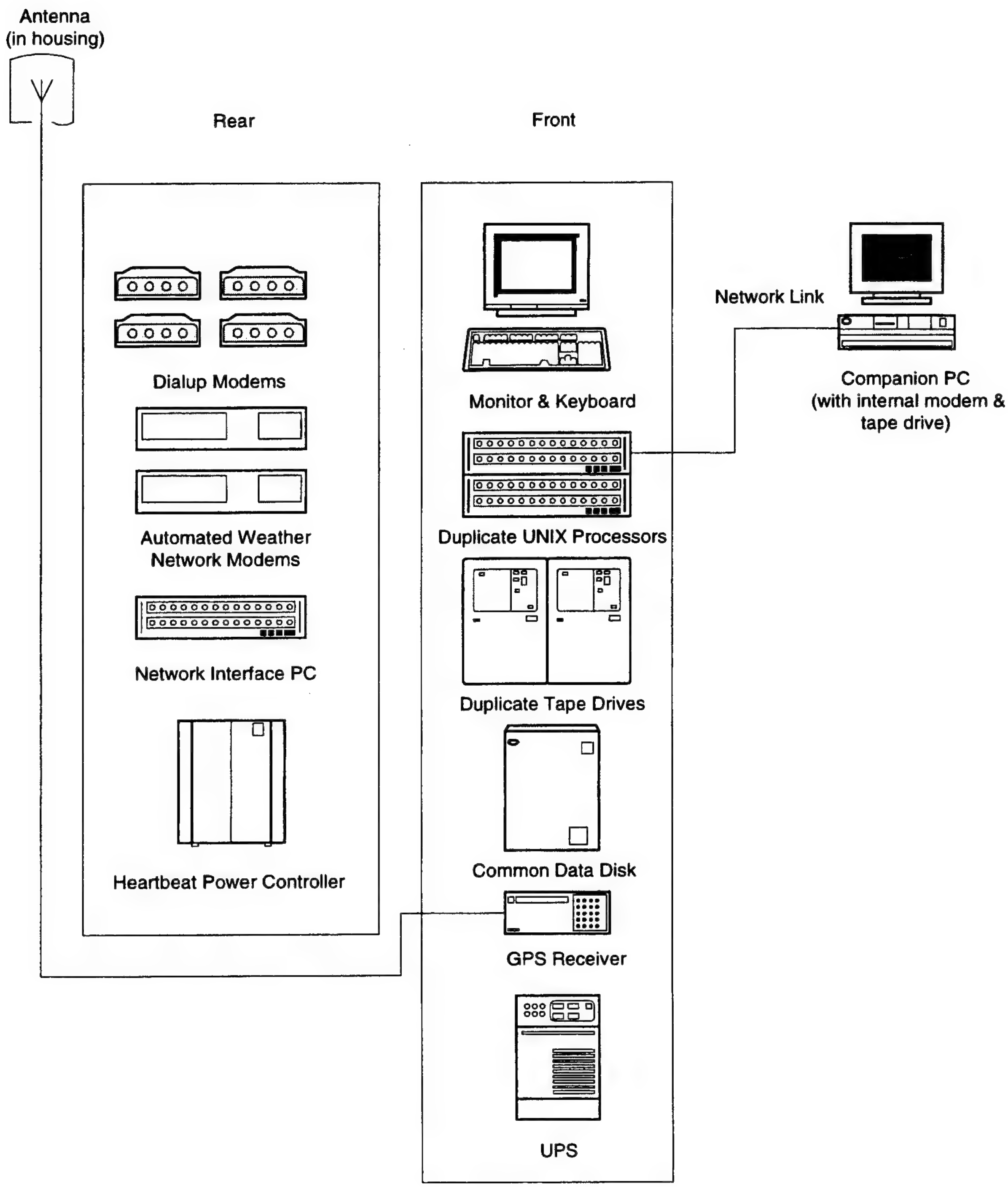

Figure 3. Configuration of IMS and Companion PC

3.1.1 UNIX System Developments

A number of system refinements, problem resolutions, and procedural enhancements were implemented for the IMS UNIX systems since their initial deployment. An automated, scheduled process was soon established to preserve the detailed TEC archive data files generated every 15 minutes, for later manual transfer to the Companion PC and subsequent storage on tape. The manual transfer procedure was streamlined considerably by development of a UNIX script, and later succeeded by a completely automated, near-real-time transfer process. The archive data file preservation on the UNIX system was retained, and a complementary process was established to delete archive files older than a specified interval, typically seven days.

The SCSI cabling between the two UNIX processors, with all of the intermediate peripheral devices, was recognized as a potential problem for system operations because of the total length of the cable and its termination in a dormant processor instead of a proper terminating connector. Consequently, for the second and subsequent IMS deployments, the physical arrangement of the IMS components was changed to reduce the total cable length. In a separate development, an electronic SCSI switch was installed to allow both processors to be at the same end of the SCSI device sequence, with a proper terminator at the other end. This added component resolved a significant problem for system operations, and its installation in the IMS at Otis resolved the SCSI cabling problem for that unit without the major rearrangement invoked for the other units.

Chronic problems were encountered with IMS UNIX operations for each Daylight Time transition, in both April and October, when the operating-system time would lose synchronization with GPS time and fail to resynchronize smoothly. This problem was resolved in advance of the October 1997 transition to Standard Time by implementing an appropriate definition for the system Time Zone, fixing the UNIX systems on Greenwich Time throughout the year.

To streamline operational and maintenance procedures, UNIX scripts were developed to allow operator communications to the UPS for diagnostic queries, without requiring changing cable connections to a separate terminal, and to reconstruct the TEC database in case of a serious file error. Separate procedures were developed to expedite offline review of the IMS log files, for the determination of system shutdown causes and operating durations.

3.1.2 Companion PC Developments

The prototype Companion PC, for Otis, was an Intel 486 PC utilizing a DOS and Windows 3.1 operating environment. Communications between the UNIX systems and the Companion PC were established using Telnet, and file transfers were performed using FTP. All activities on the Companion PC were initiated by operator control, using a remote dialup control and screen-display program. Because the DOS file system was restricted to eight-character file names, the portion of the IMS archive file names indicating the quarter-hour identifier for the file was truncated. Consequently, four quarter-hour subdirectories were established on the Companion PC, with the appropriate data files transferred to each subdirectory. This subdirectory structure

has been retained in later implementations of the Companion PC, even though the file name restriction no longer exists for the operating system being used. This subdirectory structure also is retained on the archive tapes generated on the Companion PC.

A 90-MHz Pentium PC was prepared for simultaneous deployment with the Croughton IMS, but the operating system and application software remained essentially the same as for the Otis Companion PC. By the time of the IMS deployment in Thule, six identical 120-MHz Pentium PCs were obtained for configuration as Companion PCs, and the software configuration also was revised, incorporating the Windows-95 operating system, pcANYWHERE remote control, Netmanage FTP and Telnet, and Arcada tape archiving. The extended capabilities of the revised configuration allowed automated near-real-time file transfers from the UNIX system to the Companion PC, automated tape archiving, and sufficient resources to implement some near-real-time data processing. Following the initial Windows-95 deployment to Thule, the Otis and Croughton Companion PCs were replaced by the 120-MHz Pentium/Windows-95 configurations, and the same configuration was deployed with the IMS at Shemya.

The capabilities of the near-real-time and daily processing performed on the Companion PC were expanded gradually to include many of the processing steps previously performed manually, although even many of the manual processing steps had been streamlined by the development of DOS batch files. A significant step toward this automation was the development of a BASIC program to detect the arrival of a new data file on the Companion PC from the UNIX system and initiate a sequence of several processing steps, including the extraction and accumulation of one-minute data for later use in bias calibrations, and, for the case of the Shemya IMS, the extraction of the 15-minute data report for use by the Scale Factor Generator program, which provides an ionospheric model correction factor for use by the COBRA DANE radar at Shemya. The Scale Factor Generator program runs as a separate process on the Companion PC at Shemya, having been adapted from the RTM/TI4100 version to utilize IMS data.

Preliminary provisions were incorporated into the near-real-time processing to generate a TELSI data file for transmission to 55 SWXS, as part of the preparations for replacing the AWN with the Internet-protocol Space Weather Network. This utilization of the Companion PC avoids modification of the IMS Ada code used on the UNIX system at a time when that code is under review for Year-2000 compliance.

In addition to the daily tape archiving, several automated operations are performed on the Companion PC on a daily basis. Among these are the deletion of IMS data files that have been archived to tape and various interim data files older than a designated age, generation of a daily data report containing the summary 15-minute TEC data, equivalent to the data reports transmitted to 55 SWXS, and generation of a provisional bias calibration estimate, to aid in operator evaluation of the need for a detailed receiver bias calibration.

3.1.3 Processing and Analysis

The principal operator activity for the IMS involves monitoring and recalculation of the TEC bias values assigned for the GPS receiver and the individual GPS satellites. The monitoring role is performed primarily by examination of the daily TEC profiles, as displayed from the 15-minute data, and by review of the provisional bias estimate generated daily on each Companion PC. The bias recalculation requires processing of a set of files representing the slant TEC measured from each GPS satellite during a 24-hour period.

A number of quality-checking and data-correction steps are performed prior to use of the GPS TEC measurements for the bias-calculation process. These were performed only on a manual basis at the time the first IMS was deployed, but have been augmented by data evaluation and correction programs as the number of IMS stations has increased, although a final visual certification of the data still is performed. The first step is a survey of the differential group delay (DGD) data for "wild points", which are isolated TEC values that differ considerably from the general trend of the data. The points eliminated tend to be at the beginning or end of a satellite track, when the satellite is at low elevation and the multipath effects are greater. Statistical effects arising from averaging a small number of samples in a data interval also contribute to the data variations. Short data segments, less than 45 minutes long, also are eliminated, because the subsequent phase-averaging process is degraded for such segments.

The next major step is the correction of phase discontinuities for the differential carrier phase (DCP). Small discontinuities are permitted, due to the granularity of the data sampling, and discontinuity correction is not attempted for data-sampling gaps greater than 45 minutes, although this has a detrimental effect on the phase averaging because the discontinuity then breaks the data sequence into two segments. The generally smooth behavior of the DCP data is exploited in correcting the phase discontinuities. The visual certification of the data utilizes graphical displays of the DGD and DCP data versus time, as displayed in Figure 4, with phase averaging performed to align the DCP data with the DGD data, allowing examination of the correspondence between the two sequences. Significant discrepancies between the two usually have been indicated antenna cabling problems.

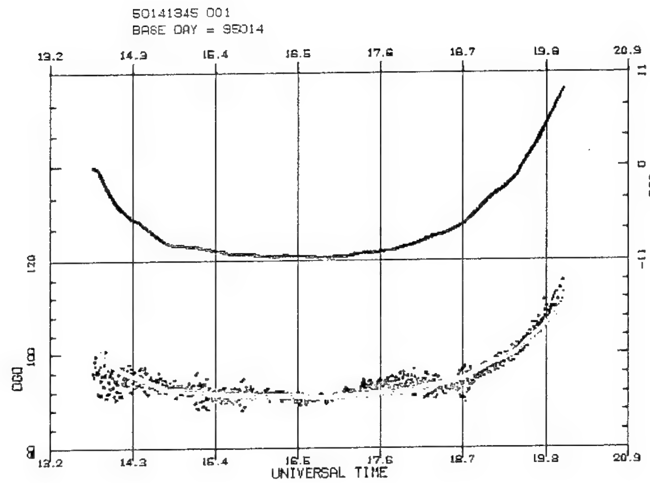

Figure 4. Differential Carrier Phase (upper plot), and Differential Group Delay (lower plot, scattered points) with Differential Carrier Phase (smooth curve) aligned using phase-averaging method.

The bias-calculation program utilizes a set of ionospheric penetration point (IPP) databases generated from the files of slant TEC data for each satellite. These databases identify the local time and latitude associated with the ionospheric penetration point for each slant TEC measurement. The bias values are determined based on correlations between derived equivalent vertical TEC measurements for different satellites at the same IPP. Originally, this determination was derived from an extensive and time-consuming least-squares minimization search algorithm, but a more efficient solution involving a matrix inversion was implemented soon after the method began to be applied for the Otis IMS on a regular basis. A number of refinements of both parameters and definitions have been developed since that transition, but the matrix inversion method has been retained throughout. A sample diurnal vertical TEC profile using calibrated data from the Otis IMS is displayed in Figure 5, for a one-degree latitude band at the site latitude.

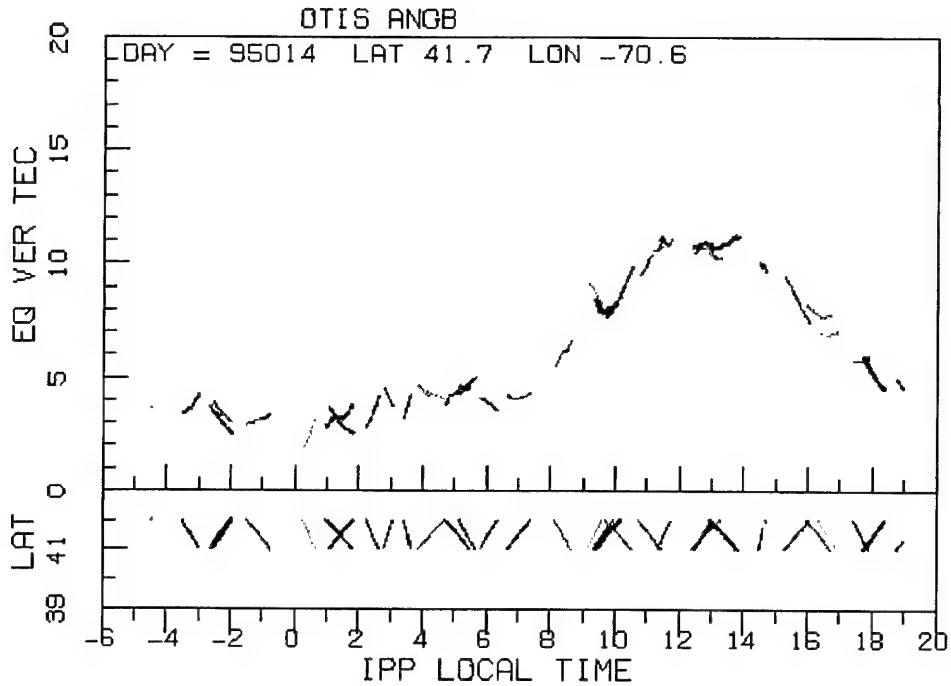

Figure 5. Equivalent vertical TEC for calibrated data at Otis IMS site latitude.

The mapping of ionospheric TEC measurements to ionospheric penetration points is performed using azimuth and elevation values derived from a GPS ephemeris almanac posted by Holloman Air Force Base, but the IMS data files contain somewhat granular values for azimuth and elevation for each satellite, derived from the GPS receiver. These soon were incorporated into the slant TEC data files derived from the IMS data, and are used to generate the IPP databases for the provisional bias calculations performed each day on the Companion PC and for the rare occasions when a detailed bias calculation is required before an almanac file is available from Holloman.

The initial implementation of bias calculations for the IMS used only the reported slant TEC measurements, which already contain corrections for the satellite and receiver biases stored in the configuration file of the UNIX system. Thus, the calculated bias values were only corrections to the nominal bias values, and a secondary process of combining the two sets was required to define new absolute bias values to be stored on the UNIX system. This process was streamlined by listing the bias values with the slant TEC measurements, and recombining the values to obtain absolute TEC measurements when the IPP databases are generated. The resulting bias values then can be converted directly to a format suitable for the IMS, without further need of a reference bias file.

The original bias-calculation method utilized correlations for equivalent vertical TEC in a narrow latitude band centered on the observing site. This technique had the disadvantage of correlating TEC measurements performed at significantly different times, corresponding to measurements at low elevation directly east or west of the observing site. A better estimation of bias values was expected if a larger latitude range was used but greater weight was assigned to pairwise comparisons with close IPP values. Early investigations indicated that the conversion to equivalent vertical TEC for lower elevations was unreliable, so an elevation threshold of 35 degrees was defined as a restriction in selecting TEC measurements. Imposition of the threshold had the further advantage of restricting the time difference between measurements, reducing vulnerability to intrinsic ionospheric variations. This revised method was employed for regular use in calibrating the IMS units.

Conditions in which some dynamic variability of the ionosphere was apparent prompted studies of the variation, primarily by means of longitudinal sections of the ionospheric vertical TEC profile. Because some variability was observed, an additional weighting factor was incorporated into the TEC correlations, representing the time difference between measurements. A study was conducted to determine appropriate parametric values for this additional weighting factor, and the revised method then was adopted for regular use with the IMS units. The highly variable conditions that can occur at Thule are not treated in a fully satisfactory manner even by this method.

Supplementary studies were performed to investigate the effects of data decimation on the computational time and accuracy of the bias calculation method. Because the data correlation is the most time-consuming portion of the calculation, the computational time decreases approximately as the inverse square of the decimation factor, while the associated bias error increases only gradually. Thus, a data sampling rate of one sample every three minutes is adequate for a bias accuracy of 0.1 TEC unit, assuming no other error sources. The parameters used for the IMS produce an effective sampling interval of 2.5 minutes, with an estimated error contribution of about 0.05 TEC unit. Plots of the computational time and bias accuracy for one decimation case study are presented in SR2.

The 15-minute TEC values from the IMS frequently would exhibit considerable scatter even soon after a bias calibration, but a bias calculation performed using the one-minute data from the same day would indicate a minimal bias shift. A study of this occurrence identified the source of the problem as long-period multipath influencing the phase-averaging adjustment as the satellite tracking progressed, so that the appropriate value for the phase-averaging adjustment was obtained only at the end of the satellite track but not during intermediate times. A partial remedy, which has been implemented, is insertion of an appropriate bias shift for each satellite so that the combined shift and multipath error is zero at the midpoint of the satellite track. A weighted compromise value for the bias shift is applied for satellites presenting multiple tracks during a day. The improvement in the 15-minute TEC values is noticeable, but observable differences from the calibrated one-minute data remain. These differences must be addressed by development of a more complete multipath mitigation.

Because IMS data originally were accumulated on a calendar-day basis, satellite tracks that spanned two days were split, causing varied multipath effects for the two portions, which changed in duration as the satellite tracks drifted with respect to Greenwich time. A number of software and procedural changes were implemented to avoid splitting data sequences at day transitions, so that complete satellite tracks are accumulated and utilized for the calibrations, unless the data-collection process is interrupted.

Another approach for eliminating multipath error uses the bias calculation process for DCP measurements only, eliminating the phase-averaging step. Each satellite track must be treated individually in this case, and the resulting bias values include the phase cycle uncertainty associated with the satellite track, but the derived TEC values could be more accurate than for the standard technique, especially if the residual multipath error after phase-averaging is greater than the intrinsic variability of the ionosphere in latitude and local-time coordinates. Unfortunately, this method cannot be applied directly to the IMS, for which near-real-time data reports are required, unless the bias-calculation method is incorporated into the IMS software. The process has been applied in test cases, giving reasonable agreement with the TEC profile derived using phase averaging, and also has been applied to single-frequency TEC determinations, with less success due to the poor quality of the slant TEC data.

The elevation threshold for selecting slant TEC measurements for the bias-calculation process has the detrimental side effect of excluding some satellite tracks completely, which can result in lack of a bias value for a particular satellite if it does not appear also on a high-elevation track. To remedy this condition, an elevation weighting factor was incorporated into the TEC correlations for the bias-calculation method. This elevation weighting factor, combined with a lower elevation threshold, also would be advantageous for near-real-time application of the bias calculation, reducing the time delay between the initial appearance of a satellite and the first estimate for its associated bias value.

A further development toward near-real-time bias calculations was inclusion of reference databases in the bias-calculation method. These reference databases can be IPP databases for which the associated bias values are known, or they can comprise completely independent measurements, or even models, of slant TEC, in the standard IPP database format. The implementation is sufficiently general to allow slant TEC measurements from an alternate site, provided that some overlap in IPP coverage exists between the two sites. This extended method was applied to a sequence of calibrations performed on six-hour intervals of data, and it performed nearly as well as a full-day calibration, except for short satellite tracks. The performance of the extended method also is much better than that of independent six-hour calibrations without reference databases.

3.1.4 Data Displays

Several different graphical display programs are utilized for examination and presentation of the TEC data and associated measurements.

The primary display program uses the IPP databases to generate several varieties of plots for equivalent vertical TEC versus local time for the IPP. Displayed data are selected by an elevation threshold, corresponding to the usual data selection for the bias calculation, or by either one-degree or three-degree latitude bands centered on the observing site. All selection parameters can be readjusted by the operator, so this program is highly adaptable for many studies.

An alternative command procedure has been developed for the same program to display equivalent vertical TEC profiles for a set of contiguous latitude bands ranging from the most southerly region observable to the most northerly region observable, a span of about 16 degrees. This provides details of the latitude gradient in equivalent vertical TEC. A similar command procedure displays the diurnal equivalent vertical TEC profile for a site partitioned into three longitude bands, situated east, overhead, and west of the site. This set of displays has been utilized for studies of temporal variability of the ionosphere.

Two diagnostic modes for the same program consist of (a) plots of slant or equivalent vertical TEC for individual IPP databases, primarily used for detailed post-processing of the calibration data, and (b) plots of data from two consecutive days in one frame, as a consistency check for individual bias calculations.

A more general diagnostic and analysis mode consists of two distinct displays of the IPP databases, used in a coordinated manner. The first display consists of one of the primary display options for equivalent vertical TEC versus local time, with a color coding for the individual GPS satellites. The second display, using the same program, consists of the satellite visibility periods versus local time, again invoking the color coding. This plot then serves as the color index for the TEC plot, facilitating the identification of GPS satellites associated with data features of interest.

Another distinct graphical diagnostic invokes many of the detailed correlation calculations of the bias-determination method and displays the correlation errors for each satellite as a function of local time. For an ideal calibration, these plots would be identical to the plots for satellite visibility periods, showing no variability in the correlations. Significant variability indicates conditions such as intrinsic ionospheric variability or slant TEC measurement difficulties, requiring further examination of the calibration process.

Displays of equivalent vertical TEC of a more global nature were developed in Interactive Data Language (IDL), again utilizing the IPP databases. One display mode is a surface plot of equivalent vertical TEC versus latitude and local time for an entire day, while the other display mode is a contour plot for the same variables. In both cases, IDL routines are used to reconcile discrepant equivalent vertical TEC determinations at the same coordinates and to interpolate equivalent vertical TEC values for coordinate regions lacking coverage.

Some of the display formats for the IPP databases have been replicated for the 15-minute data reports, to allow validation of the 15-minute data and to permit utilization of these data in

monitoring efforts for the IMS. In addition to the plots of equivalent vertical TEC versus local time and plots of satellite visibility periods, plots of the minimum and maximum equivalent vertical TEC values in a 15-minute interval also can be generated. Provisions exist for the display of standard-deviation values over 15-minute intervals, but these plots are used only infrequently. These display capabilities also have been implemented for a 15-minute data format in use at 55 SWXS, as a precursor to the current display programs developed there.

As described in a previous section, visual certification of the TEC data is performed as part of the bias calculation process. In addition to the composite DGD and DCP plots mentioned there, several other displays based on the same data format were developed. Separate plots of DGD and DCP versus time, without the phase averaging or superimposed data sequences, can be generated, especially when only black-and-white printed plots are needed. An augmented form of these plots includes the satellite elevation and azimuth, but sacrifices some detail for the ordinates. A format used for multipath-amelioration studies displays only the DGD, which is significantly affected by multipath, and the elevation, which tends to be the principal parameter for the magnitude of the multipath. The multipath pattern itself is displayed as the difference between the DGD and DCP data, considering the almost complete absence of multipath effects in the DCP data.

Detailed data at a 2-Hz sampling rate are available in the IMS archive files, and capabilities for examining these data have been developed, primarily for diagnostic studies. Except for one plot format displaying receiver channel versus GPS satellite number, all plot formats use time as an independent variable, in its raw form from the receiver as seconds during the week. The various groups of variables that are displayed as data sets are as follows:

a) DGD, DCP, Warning flags (L1 and L2), and Elevation;
b) DCP, Elevation, Azimuth, and Signal Strength (L1 and L2);
c) Satellite Number, DGD, Warning Flags (L1 and L2), and Receiver Channel;
d) Receiver Channel.

Several graphical displays were developed for data other than TEC or receiver data, but which are ancillary or derived parameters for the GPS measurements. The two principal categories of such parameters are the combined satellite and receiver bias values and the satellite ephemeris parameters.

A utility program calculates the mean bias, as well as the standard deviation, over all satellites for the provisional bias calculation performed on the Companion PC, and these values are plotted on a cumulative daily basis to ascertain bias variations and the possible need for a detailed calibration. Individual bias values for each satellite also can be plotted, and the consistency of this pattern provides a further validation of the bias calculation, because the individual satellite biases tend not to change relative to each other, although the receiver system bias does produce a change in the absolute bias levels.

The azimuth and elevation values derived from the Holloman almanac files can be plotted as abscissa and ordinate pairs to produce a representation of the GPS satellite sky tracks. This format has been used to examine sky coverage patterns and effects of local obstructions. The time tags associated with these azimuth and elevation values provides information used for a display of the predicted satellite visibility periods, in a format identical to that used for the measured data, thus providing a simple and efficient means for detecting missing satellite tracks or other deficiencies in satellite coverage. The principal orbital parameters of semimajor axis, inclination, and right ascension of the ascending node, as derived from either the Holloman almanac or the broadcast GPS message, can be plotted for each satellite. This format was developed to facilitate the detection of "ghost" GPS satellites, which occurred when an existing GPS satellite was incorrectly associated with a different satellite number, which may or may not correspond to an actual satellite. A further discussion of "ghosts" is presented in the next section.

3.1.5 Data Diagnostics

Four significant data problems were investigated for the IMS. One of these, variability of the 15-minute data, was discussed in Section 3.1.3 and has been resolved only partially, requiring some form of multipath mitigation for complete resolution. The first problem detected, soon after initial IMS deployment at Otis, was the occurrence of spurious GPS satellite observations, either for satellites that did not exist, satellites that should not have been visible at the time of the observation, or satellites that were visible but were reported at an incorrect position. These occurrences were dubbed "ghosts" and were investigated both separately and in conjunction with another significant problem, substantial TEC outliers. The fourth significant data problem was detected only after close daily monitoring of the IMS was established; it appeared as a substantial bias shift for a single satellite for a single passage across the sky. This phenomenon was designated as "anomalous biases".

The "ghost" problem was significant for its generation of spurious TEC values in data reports to 55 SWXS. Most of the "ghost" occurrences were of very short duration and could be excluded on this basis, but some appeared as precursors to appearance of an actual satellite and could be excluded only with difficulty. The problem was isolated to the receiver and antenna subsection of the IMS units, by capturing data directly from the receiver during IMS operations using a special data link developed and installed by CSDL. The problem then was associated with the original IMS Micropulse antenna by means of an experiment utilizing the Real-Time Monitor (RTM) system at Otis with an Ashtech receiver and antenna. No "ghosts" were detected with the RTM system until the antenna connections were exchanged with the IMS, and the IMS ceased reporting "ghosts" while using the Ashtech antenna.

Further experiments at Hanscom confirmed the association of "ghosts" with the Micropulse antenna, while also eliminating the IMS antenna housing as a cause. Consequently, all of the Micropulse antennas for the deployed IMS units were replaced with Ashtech antennas during scheduled maintenance visits to the IMS sites. Discussions between AFRL personnel and Ashtech staff have indicated that the "ghosts" arise with high gain levels on the antenna input to

the receiver. This association confirmed an earlier conjecture by NWRA personnel that the "ghosts" may be associated with antenna gain, because the sources for "ghosts" from the Micropulse antenna were traced to high-elevation satellites, where the antenna gain is higher, and the Ashtech antenna was found to have overall less gain than the Micropulse antenna.

Significant TEC outliers were found to occur independently of the occurrence of "ghosts." Some of these were associated with initial discrepancies in the measured DGD attributed to multipath and larger relative noise values at low elevations, but these were not among the largest outliers. Detailed examination of the 2-Hz IMS data established an association between extreme DGD values and non-zero values for the data-quality warning flags for the two GPS frequencies, so CSDL personnel implemented a change in the initial data-processing stages to check the appropriate flags before utilizing the data for time averaging. The magnitude of outliers was reduced greatly by this change, but smaller outliers still occur at the beginning and end of satellite tracks due to the small number of data samples that sometimes constitute nominal one-minute and 15-minute data samples. Discussions with AFRL personnel were conducted to define appropriate exclusion criteria for 55 SWXS to eliminate these remaining cases upon receipt of the data reports. NWRA personnel also instituted more detailed examinations of the data-quality flags to accommodate an Ashtech receiver firmware upgrade.

One set of significant TEC outliers remains, and has been associated exclusively with the IMS at Thule. For these rare cases, there appears to be an undetected loss of lock for phase, so that a substantial phase discontinuity occurs without setting the appropriate flag. Normal time averaging and phase averaging are performed, resulting in a sharp TEC change with only a slow decay with time. Preliminary investigations have been conducted, but the problem remains unresolved.

A number of investigations were conducted to determine the source of the "anomalous bias" problem, which poses a distinct obstacle to routine utilization of the IMS data reports, because the magnitude of the anomaly is typically on the order of 100 TEC units. The possibility of a true satellite problem was excluded by simultaneous observations of a single satellite from two distinct IMS sites, with an "anomalous bias" being observed from only one of these sites. The anomaly also appears in the earliest available data stored by the IMS, before the bias corrections are implemented, and therefore cannot arise from an error in acquiring the bias configuration table. The pattern of the multipath in the DGD is also unchanged when an "anomalous bias" occurs, nor is the problem associated with a particular receiver channel. The occurrence of the problem does not appear to be associated with an excessive number of visible GPS satellites, nor with a particular direction in the sky. Direct data capture from the receiver again isolated the problem to the receiver and antenna subsection of the IMS units, after over five weeks of monitoring.

A firmware upgrade was arranged by AFRL personnel, and three of the spare Ashtech receivers were upgraded to the 1G02 level, but the upgrade failed to resolve the "anomalous bias" problem. The occurrence of "anomalous biases" for other Ashtech systems was confirmed by discussions between AFRL personnel and researchers at the University of Texas Applied

Research Laboratory supporting the National Imaging and Mapping Agency, and a further firmware upgrade was initiated by AFRL, but definite results concerning the resolution of this problem are not yet available.

3.2 IMS Operations

The 15-minute TEC data reported by the IMS were plotted for each day at each site, to monitor the calibrations, data anomalies, and changes in the active GPS constellation. Tapes were catalogued for content and indexed for local storage upon arrival at AFRL each month.

GPS ephemeris files were retrieved from Holloman AFB on a weekly basis, for use in determining the apparent sky positions of GPS satellites and the associated IPP coordinates, which are used by the bias determination process.

A summary log was maintained for the Otis IMS, the Croughton IMS, the Thule IMS, and the Shemya IMS, primarily to monitor the duration of operations for each of the two UNIX computer systems in each IMS. The cause of the system shutdown also was recorded in this log. A histogram of system operating durations, by month, is included in this summary log for each IMS, with a summary table displaying the total percentage of operating time for each month and the number of occurrences of various outage causes.

Data files were retrieved from the IMS sites and were used to evaluate performance of the current bias definitions for the IMS and to calculate revised bias values for installation on the IMS. These data also are reviewed for anomalous and spurious TEC measurements, as part of the assessment of the IMS performance. Preliminary notification was received in March 1997 from 55 SWXS that the IMS data soon would be utilized for model applications. Consequently, a regular schedule of calibrations was established, so that the individual sites were re-calibrated no less often than once every two weeks, and sooner if circumstances or data results indicated a need. Operational status for the IMS data utilization was declared by 20 June 1997, with the data being applied by 55 SWXS to calculations for the Parameterized Ionospheric Specification Model.

3.3 IMS Database

The archived IMS data are stored on data tapes at AFRL at Hanscom to support retrospective studies of IMS performance and other ionospheric analysis and modeling efforts. An index of the data tapes received from each IMS site is maintained as part of the IMS operations, so that any specified day of data can be retrieved quickly. The data files are stored in the same format in which they are generated on the IMS, so the standard IMS data-processing programs can be applied to extract and process the archived data. Some of the data tapes have been transcribed to CD, to enhance accessibility for the data files.

Three distinct types of data are contained in each IMS data file, associated with the three different data sampling intervals: 0.5 seconds, 30 seconds, and 15 minutes. Supplementary

ephemeris data, derived from the GPS message, are stored with the 15-minute data. The 30-second data samples contain overlapping one-minute averages of slant TEC values, while the 15-minute data samples are derived from the 30-second samples contained within each disjoint quarter-hour interval. A summary description of the data values is given in Table 1.

Table 1
Contents of IMS Data Files

0.5-second Sampling Data

Milliseconds of GPS Week (msec)
Satellite PRN
Tracking Mode
Satellite Elevation (degrees)
Satellite Azimuth (two-degree units)
Receiver Channel (1 - 12)
L1 Warnings Status Word
L1 Phase Quality Indicator
L1 Carrier-to-noise Ratio
L2 Warnings Status Word
L2 Phase Quality Indicator
L2 Carrier-to-noise Ratio
Code-based TEC (TEC units)
Phase-based Relative TEC (TEC units)

30-second Sampling Data

GPS Week Number
Milliseconds of GPS Week (msec)
Satellite PRN
Tracking Mode
TEC Sample Size
Delta-TEC Sample Size
Loss of Lock Count
Length of Phase Averaging
Satellite Elevation (degrees)
Satellite Azimuth (two-degree units)
L1 Phase Quality
L2 Phase Quality
L1 Carrier-to-noise Ratio
L2 Carrier-to-noise Ratio
Code-based TEC (TEC units)
Phase-based TEC (TEC units)
Phase-averaged TEC (TEC units)

Equivalent Vertical TEC (TEC units)
Satellite Bias (sec)
User Equipment Bias (sec)

15-minute Sampling Data

GPS Week Number
Time of Interval Midpoint in GPS Week (msec)
Time of Maximum Vertical TEC (msec)
Satellite PRN
Quality Words (5)
Loss of Lock
Latitude of IPP at Midpoint (degrees)
Longitude of IPP at Midpoint (degrees)
Latitude of IPP at Maximum Vertical TEC (degrees)
Longitude of IPP at Maximum Vertical TEC (degrees)
Maximum Equivalent Vertical TEC (TEC units)
Minimum Equivalent Vertical TEC (TEC units)
Average Equivalent Vertical TEC (TEC units)
TEC Standard Deviation (TEC units)
[Ephemeris Data Record]
TISS Position Data (x,y,z; ECEF Coordinates, m)

Ephemeris Data (Individual Satellites)

GPS Week Number
Time of GPS Week (msec)
Group Delay (sec)
Clock Data Issue
Clock Time (sec)
Time Adjustment (quadratic coefficients; sec/sec**2, sec/sec, sec)
Orbit Data Issue
Correction to Average Motion (semi-circles/sec)
Mean Anomaly (semi-circles)
Eccentricity
Square Root of Semimajor Axis ($m^{1/2}$)
Epoch Time (sec)
Harmonic Correction CIC (radians)
Harmonic Correction CRC (radians)
Harmonic Correction CIS (radians)
Harmonic Correction CRS (radians)
Harmonic Correction CUC (radians)
Harmonic Correction CUS (radians)
Longitude of Ascending Node (semi-circles)
Argument of Perigee (semi-circles)

Inclination (semi-circles)
Ascending Node Rate (semi-circles/sec)
Inclination Rate (semi-circles/sec)
Accuracy Code
Health Code
Fit Interval Code
Satellite PRN

Except for some outage occurrences and rare instances of unreadable archive tapes, the data archive exists for the Otis IMS, Shemya IMS, and Thule IMS from their deployment dates. Outages for the Otis IMS data archive during its initial operations were more frequent than normal until the Companion PC archiving process became fully operational, while the initial year of IMS operations at Croughton was detrimentally affected by software problems associated with the AWN communications.

3.4 Scintillation Observations and Simulation

Trimble Pathfinder measurements of GPS signal strength, conducted in Chile during 1994, were correlated with relative TEC measurements derived from the same receiver and with airglow images of plasma-density depletion regions. An analysis was performed, assuming vertical extents for the depletion regions, to examine the three-dimensional structure associated with the scintillation occurrences.

TEC decreases consistently were associated with depletion regions identified in the airglow images, and scintillation occurrences were associated more closely with the edges of TEC depletions. For the simple three-dimensional structure assumed for the depletion regions, the regions associated with scintillation could be as high as 600 km and as low as the visual airglow altitude of about 250 km. Alternative interpretations are that the TEC depletion and scintillation-generating regions are tilted to the west or that they have an irregular horizontal structure at different altitudes.

Data collected by the RTM/Ashtech and Trimble Pathfinder receivers during the March 1997 Ascension Island campaign were transferred from the collection systems to local computers. The Trimble data were reviewed for scintillation occurrences, while the RTM data were to be used to calculate TEC values. Loss of the DCP data for the RTM prevented adequate calibration of the TEC data, despite several attempts at utilizing only the DGD data.

Novatel scintillation measurements were examined during its testing period at Hanscom and after its deployment to the HAARP site in Gakona, Alaska, but no instances of scintillation were observed. The irregular effective horizon presented by nearby buildings, together with the associated multipath irregularities, made interpretation of the scintillation index values difficult when viewed as a time sequence for individual satellite tracks. A sky survey display was developed, with the size of the plotted symbol representing the scintillation index value. The pattern of variability was found to be quite regular, except for the period when the antenna was blown off the roof of the trailer housing the data-collection systems. A sample plot is displayed as Figure 6.

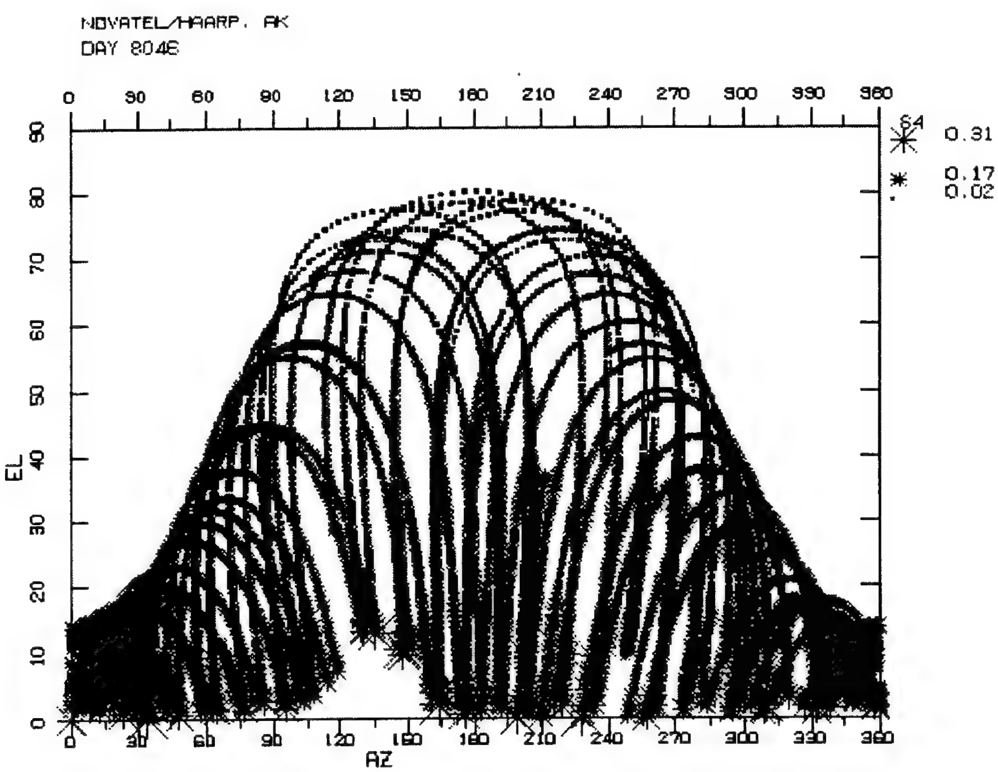

Figure 6. Novatel scintillation survey chart, showing typical coverage and variability without scintillation.

A statistical simulation of scintillation effects was developed for use by the Wright Laboratory at Wright-Patterson AFB (now part of AFRL) with their Antenna Wavefront Simulator (AWFS), to provide realistic scenarios of sustained scintillation levels more severe than those experienced for current solar conditions. The basis for the simulation is the "six sigma" model (Fremouw et al, 1980), with the cross-correlation standard deviations currently being defined as zero. Reasonable simulation results have been obtained for the scintillation scattering component, and the structure for the geometric optics component of the scintillation also has been developed. Further analysis was performed to define the parameters for the geometric optics component. The resulting scintillation spectra, intensity variations, phase variations and complex-plane scatter plots were evaluated; they displayed a reasonably good correspondence to actual VHF scintillation, as indicated by the intensity and phase power spectra displayed in Figures 7 and 8. Seven sets of simulated data were transmitted to Wright Laboratory for testing of four GPS receivers during the last week of June 1997.

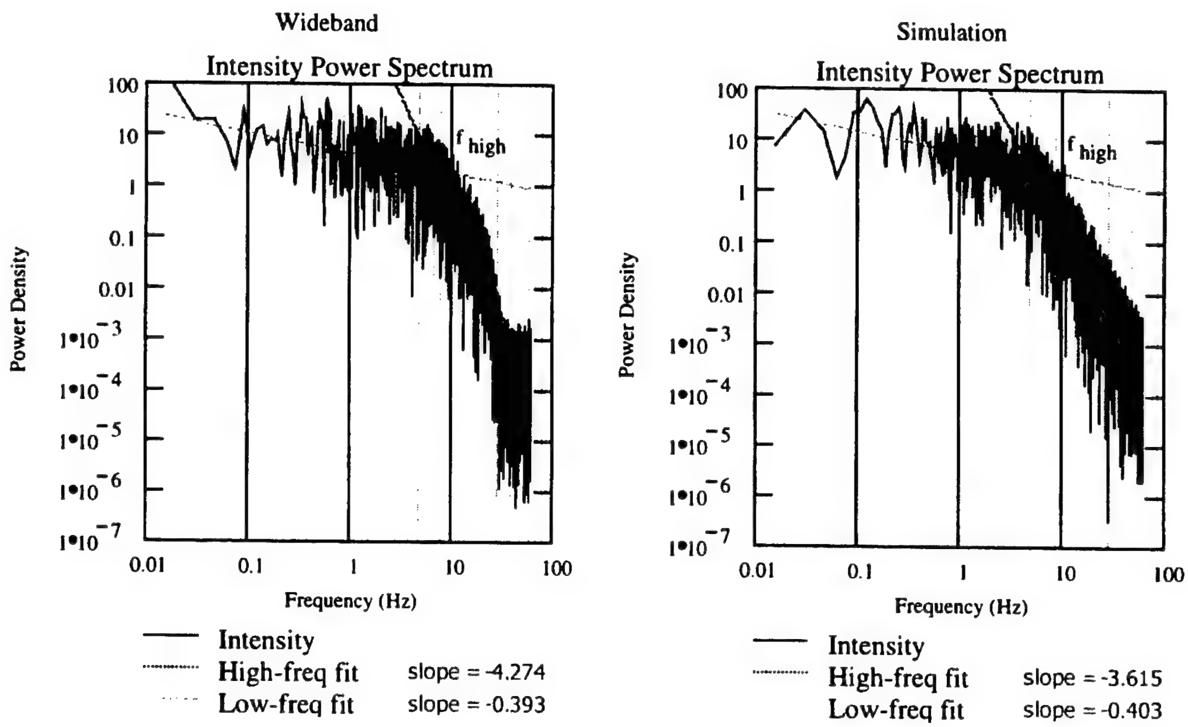

Figure 7. Intensity power spectra for Wideband VHF data (left) and simulation (right).

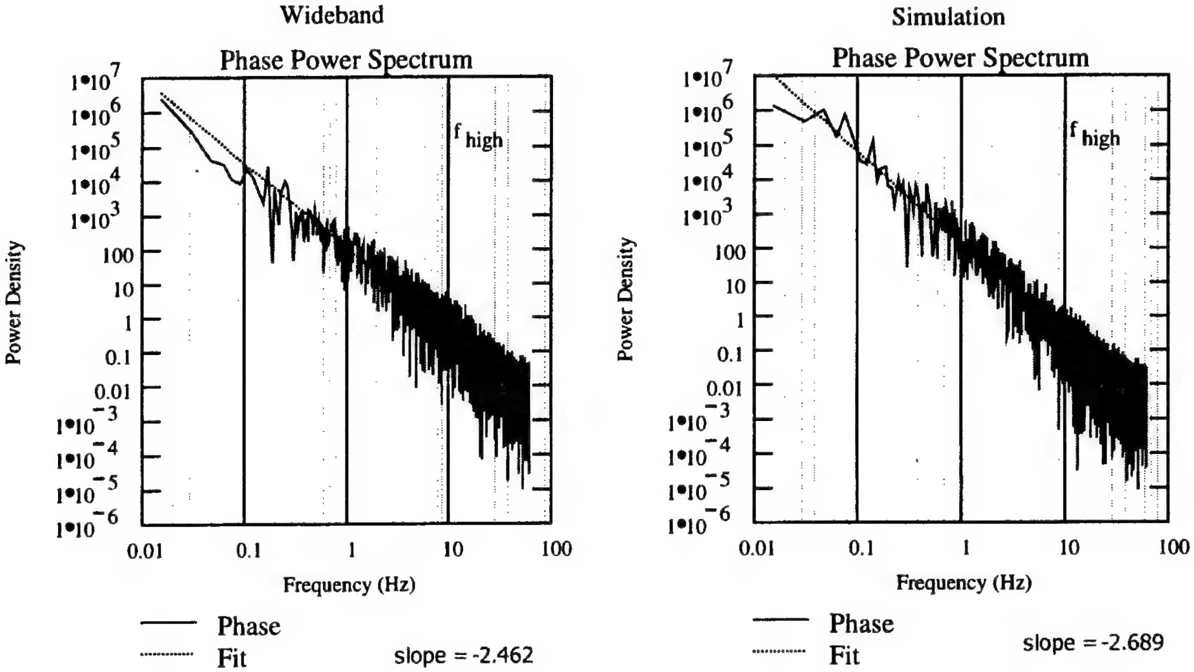

Figure 8. Phase power spectra for Wideband VHF data (left) and simulation (right).

4. Ionospheric Model Assessment

The Parameterized Ionospheric Model (PIM) [Daniell, et al, 1995] was used to calculate three-dimensional profiles of electron density, for general evaluation of its diurnal pattern and for more detailed assessment of its plasmasphere component. The apparent location and amplitude of the equatorial anomaly, as depicted in three-dimensional plots, changes with longitude, sometimes producing a secondary density maximum. A more appropriate representation of this variation would be by the use of geomagnetic coordinates, but this would have required regenerating all of the density profiles and reprocessing them for three-dimensional viewing. The altitude variation of the peak density of the equatorial anomaly, which appears to be about 100 km, is of some concern for implementation of the bias-calculation method, which assumes an altitude of 350 km for the conversion of slant TEC measurements to equivalent vertical TEC. A greater concern for the bias calculation is the plasmasphere, which was examined by differencing PIM calculations performed with and without its Gallagher plasmasphere component [Gallagher, 1988] activated. Although the Gallagher model is formulated in L-shell coordinates, its vertical density profile and TEC latitudinal profile appear to be adequately approximated by relatively simple functions (Chapman or double-exponential and Gaussian, respectively) of geomagnetic coordinates, so that some accommodation can be performed within the bias calculation for the plasmasphere contribution. This extension of the bias-calculation method remains to be implemented.

PIM also was implemented in a command procedure to display diurnal profiles of TEC for the IMS sites, for comparison to measurements. The general features of the diurnal profiles measured at the IMS sites are apparent in the PIM profiles, but the relative local times of primary and secondary TEC maxima often are reversed in the PIM profiles with respect to the measured TEC, and the relative amplitudes of these local maxima also are different between PIM and the measurements. The variability of the Thule TEC measurements is not represented in the PIM profiles, but they do provide a basis for visualizing the underlying diurnal variation in the Thule TEC measurements. It should be noted that the PIM profiles are only calculated monthly using forecast climatological parameters, in the same manner as the Bent-model tables used for the COBRA DANE radar range-and-refraction corrections, so that a closer correspondence between PIM and measured TEC might be obtained if measured daily parameters were used for the PIM calculations. This degree of detail was beyond the intended scope of this development.

5. Space Weather Workshop

AFRL and ONR collaborated with the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA) in developing a workshop regarding "Space Weather Effects on Propagation of Navigation & Communication Signals," held at COMSAT Corporation in Bethesda, MD, in late October. Along with AFRL staff members David Anderson and Edward Weber, NWRA scientist James Secan participated as a member of the workshop steering committee, chaired by NWRA scientist Edward Fremouw (under NSF and NOAA sponsorship).

Mr. Secan organized a poster session at which 28 sets of user-oriented research results and space-weather products were displayed. He and NWRA consultant A. Lee Snyder served as co-recorders of focus-group discussions on Commercial Space Weather Services. AFRL staff members Greg Bishop and Keith Groves respectively recorded focus-group discussions on Navigation and Communication systems effects. With the assistance of NWRA consultant John Rasmussen, Dr. Fremouw organized and chaired a plenary session at which the focus groups reported back to the assembled participants and other aspects of the workshop.

6. HAARP Activities

Under HAARP, a world-class observatory is being constructed at Gakona, AK, to conduct upper-atmospheric, ionospheric, and radio-propagation research. At Gakona, a high-power HF transmitter is being installed by Advanced Power Technologies, Inc. (APTI). Along with other research organizations, NWRA is participating in and coordinating installation of an array of geophysical diagnostic instruments. Our efforts involving HAARP diagnostics are reported in Subsection 4.1. We summarize other HAARP activities in Subsections 6.2 and 6.3. More detailed descriptions of those activities, carried out by Rasmussen and Snyder, are provided in a consultant report attached hereto as an Appendix.

The first major research campaign involving HAARP, consisting primarily of ULF/ELF/VLF experiments during active ionospheric conditions and measurements of

stimulated electromagnetic emissions (SEE) during quiet periods, was conducted between 24 February and 14 March 1997. A new diagnostics center, including a road and instrument-shelter pads, is in place for the next major HAARP campaign, at which time it is hoped that the HF transmitter will be operated at 960 kW.

6.1 Development of HAARP Diagnostics

NWRA's activities related to development of HAARP diagnostics included participation in or coordination/facilitating the installation and/or operation of several instruments, as summarized in the following subsections.

6.1.1 30-MHz Riometer

Departure of the riometer principal investigator (P.I.), Jens Ostergaard of Boston College, created a problem with interpretation and control of data quality. NWRA assumed responsibility for operation of the instrument, with AFRL handling quality control. Under a separate contract, NWRA has engaged Mr. Ostergaard as a consultant to analyze the riometer data.

Under the present contract, NRWA personnel reviewed riometer processing programs and processed a backlog of data from the period January through October 1996. Some aspects of the data-processing procedure were automated, which included development of a new program to generate printed plot copies automatically. This development required an upgrade for the software device drivers to support the color printer being used. The programs were all installed and tested on the Windows/NT PC that was configured for use at the HAARP site. Some difficulties with the video display for the plotting programs were encountered and overcome.

6.1.2 Imaging Riometer

The imaging riometer operated by the University of Maryland (UM) was reinstalled at Gakona. Researchers from UM developed software to calculate the quiet-day curve on site and to provide absorption displays in real time. Previously, the local display had represented the total riometer output, and absorption values had not been determined until the data were returned to Maryland.

6.1.3 Spaced-antenna Scintillation Monitor

Operation and display software for a Scintillation Monitor was demonstrated at SRI International early in 1997, including a remote display at Hanscom. Following the demonstration, it was decided to install the system at HAARP for the March HIPAS/HAARP campaign. Mr. Robert Livingston – then of SRI International, now of Scion Associates – installed this eight-antenna system on site during the campaign. He and John Rasmussen subsequently identified a more suitable location for the array. Under a separate contract, NWRA is facilitating acquisition of facilities at the new location, in Slana, AK.

6.1.4 Ionosonde

The configuration, installation, and price of an appropriate antenna for the HF Ionosonde was discussed with the University of Massachusetts at Lowell's Center for Atmospheric Research (UMLCAR). A substantial variety of antennas was found to be available for consideration. Subsequently, NWRA developed specifications for transmitter-antenna towers to be erected at Gakona and coordinated their acquisition. Installation of the towers and other diagnostic instruments was to have taken place in the summer of 1997, but road construction to the diagnostics site was delayed. Consequently this contract was extended (at no incremental cost) so that installation could take place during the Alaska construction season of 1998.

In May, 1998, NWRA Research Engineer J. Francis Smith traveled to Gakona to initiate tower installation. The support system for the transmitter antenna consists of a 120-foot central tower and four 60-foot towers arrayed symmetrically about the center one. The center tower is made up of six 20-foot sections having triangular cross sections 30 inches on a side and made of welded, galvanized steel. The outer towers are made up of three 20-foot sections with side dimensions of 18 inches.

The ionosonde site consists of muskeg forest underlain with permafrost. Each tower is supported by a pipe set into the permafrost, with a baseplate and shear pin welded to its top. Each baseplate is about four feet above grade. Each tower also is guyed to three anchor cables set into the permafrost. Each foundation pipe is surrounded by a gravel pad approximately 20 feet in diameter and two feet deep, and a pathway was made of the same material. After thaw, vehicle access is physically difficult and environmentally costly.

Previously, a description had been sent to three prospective installation firms, including site drawings from the USKH civil engineering firm and component and engineering drawings from the tower manufacturer, Fred Nudd Corp. The three bidders, all located in Anchorage, were well known to HAARP personnel and had performed satisfactorily. The winning (low) bidder, Newberry Alaska, proposed to perform the installation by pre-assembling the tower sections and guys on the ground and then hoisting the assemblies by means of a helicopter; the other bidders proposed more conventional installation methods.

Installation of the four smaller towers proceeded as planned, with the contractor crew arriving on site on 13 May. The six tower sections were assembled on the roadway near the antenna site by means of a boom truck belonging to the contractor. The guys were attached and secured with quick-release ties. The center tower was assembled for a 'two-pick' installation, the lower 60' (with its guys) and the upper 60' being assembled separately.

The helicopter arrived the following morning, and after a safety briefing, began its work. The first tower took about 30 minutes of air time, the last three took about 15 minutes each. With helicopter costs accruing only while flying, the helicopter landed after each installation. When each tower section was ready for pickup, the helicopter hovered over it while a lineman attached its hoist line to a matching line from the tower and then moved away. The helicopter

then drew the tower into a vertical position and lifted it. The pilot then flew a pattern selected to bring the tower into position against the prevailing wind. While hovering, he then lowered the tower until the ground crew could guide it onto the top of the foundation pipe. With the helicopter holding the tower vertical, the three linemen cut away the quick-release ties on the guys, and each ran with his guy to the appropriate ground anchor cable and secured it. The pilot then released the hoist hook, and the linemen set the tension on the guys. Each placement, including setting the tension, took one to two hours.

Installation of the center tower went far less smoothly. An error on the engineering data sheet received from the tower manufacturer grossly understated its weight, which required a larger helicopter. To minimize the resulting cost impact, NWRA and Newberry delayed installation of the center tower until the required helicopter was in the Gakona area for other purposes. On 28 July, the Newberry crew arrived on site to prepare for the installation. The helicopter arrived on schedule the next morning. While installing the lower 60-foot section, another error was discovered. The guy anchors were not 118 feet from center, as indicated on a drawing provided by AFRL, but rather 150 feet.

On Friday, 31 July, additional guy wire was brought in, and the lower section of the center tower went up. As the upper section was being maneuvered into place, sufficient difficulty was encountered that the installation contractor halted the operation out of concerns for personnel safety. On Monday, 3 August, Frank Smith sketched a guide assembly designed to allow a more controlled mating of the two sections and faxed it to the contractor in Anchorage from NWRA in Bellevue, WA. After discussions, it was agreed that a similar guide would be fabricated in Alaska rather than in Washington to ensure that it would fit the actual tower (rather than relying on the tower drawing).

By 2 September, the guide had been fabricated, and it was transported to the HAARP site and attached to the tower. The helicopter pilot was thoroughly briefed on the expected sequence of events, and the installation was completed smoothly. The tower was leveled and the guys tensioned without incident. The tower installation is now complete and awaiting installation of the transmitter antenna by AFRL personnel. The ionosonde and its receiver antenna also will be put in place by AFRL.

6.1.5 GPS Receiver

NWRA installed AFRL's Novatel receiver at Gakona for measurement of TEC and amplitude scintillation. (See sky-coverage chart in Figure 6.) The Novatel, which receives an L-band signal transmitted from GPS satellites, provides samples along a few slowly moving lines of sight through the Alaskan ionosphere. NWRA developed software to convert the Novatel data to netCDF format and archive it in the HAARP database.

Procedures were developed by NWRA to process and display current Novatel data on-site, in preparation for a site visit in late June of 1997 by personnel from the office of the Secretary of the Air Force (SAF). Some enhancements were incorporated in the on-site computer to support

these extended processing capabilities. John Rasmussen supported the SAF visit, including preparation of data displays and presentation of the diagnostic area. AFRL now has taken over direct responsibility for operation of the Novatel and archiving of its data.

Future installation, under a separate contract, of an NWRA ITS10 receiver at Gakona will permit reception of phase-locked VHF/UHF signals transmitted by the Transit satellites of the Navy Ionospheric Measuring System (NIMS). The latter will augment the quasi-continuous GPS sky samples with quasi-snapshots in the form of detailed latitudinal scans of TEC and of attendant phase fluctuations during passes of several Transits. NIMS was formed upon decommissioning of the Navy Navigation Satellite System at the end of CY 96, with the transmitters being left on for purposes of ionospheric research.

6.1.6 ULF/ELF/VLF/LF Receivers

HAARP has two primary ELF/VLF receivers, which are located at Gilmore Creek and Delta Junction, AK. For the 1997 campaign, a third receiver was located close to Gakona for ELF experiments there. The additional receiver was assembled by personnel from APTI and the University of Alaska at Fairbanks (UAF), and it provided the first measurements of ionospherically generated ELF using the HAARP HF transmitter.

6.1.7 Optical Imager and Instrument Shelter

Under a subcontract from NWRA, UAF developed the HAARP Optical Instrument Shelter (OIS), and it was installed during early in 1997. NWRA Project Engineer C. Charley Andreasen installed an optical fiber link between the OIS and the HAARP Operations Center, and NWRA arranged for regular telephone service to the OIS and to the ELF site at Delta Junction. The HAARP optical imager was installed in the OIS and has operated well.

6.1.8 Other Diagnostic Activities

In addition to the foregoing, NWRA consultants coordinated operational efforts and development of data displays for (a) Scion Associate's spaced-antenna scintillation monitor and (b) the magnetometer and ELF/VLF receivers operated by UAF personnel. John Rasmussen and Lee Snyder continued to represent diagnostic interests in development of infrastructure at the HAARP site.

6.2 Facilitation of HAARP Operations and Broader Scientific Collaborations

At the request of the National Science Foundation (NSF), Lee Snyder and NWRA Consultant Professor William E. Gordon drafted a charter for an incoherent-scatter radar (ISR) design panel. The main purpose of the design panel was to identify approaches for meeting the science requirements defined in the final report of the NSF/HAARP ISR Requirements Panel. Subsequently, Dr. Snyder drafted, coordinated, and finalized the ISR Design Panel's report. The report was distributed only to the Panel sponsors (NSF, ONR, and AFRL), as it contains information that may be source-selection sensitive. It reviews various design approaches and

weighs the issues for developing an ISR. A mechanical approach was developed for a 110-meter-diameter, planar, receive-only array. The mechanical approach was made available for HAARP site planning.

NWRA consultants organized the 1997 and 1998 RF Ionospheric Interactions Workshops, held to develop coordinated research campaigns for the HAARP, HIPAS, and Arecibo facilities. These workshops were two in an on-going series aimed at making the most effective use of available resources, including diagnostic instruments. NWRA continues to present, monitor, and resolve issues associated with diagnostics and research campaigns at the Program Management Review meetings held each month with the transmitter contractor, APTI.

6.3 Public Relations

Two-day open-house events were held at the Gakona facility in August of 1997 and 1998. The second and third in a series of such annual events, they attracted over hundreds of attendees, featured presentations on the status of the HAARP Ionospheric Research Observatory, including transmitter construction, diagnostics, spectrum monitoring, and environmental compliance. NWRA participated by providing the consulting services of Professors William Gordon of Rice University, Michael Kelley of Cornell University, and Lewis Duncan of Dartmouth College to answer questions about the ionosphere and to address public concerns about the facility. In addition, NWRA Sr. Research Scientist Edward Fremouw prepared and presented poster discussions of TEC and scintillation observations as HAARP diagnostics at the 1997 open house, and Lee Snyder prepared and presented posters specifically dealing with HAARP and on the more general topic of Space Weather.

Additional support regarding public relations was provided via preparation of regular announcements of HAARP activity that appear in the Copper River Country Journal and in developing an educational outreach program between the Glennallen High School and the UAF's Geophysical Institute.

7. Publications

The following publications resulted, in part, from research carried out under this contract.

Bishop, G., A. Mazzella, E. Holland, "Application of SCORE Techniques to Improve Ionospheric Observations," Proceedings of ION GPS-95, Institute of Navigation, Alexandria, VA, 1995.

Bishop, G., A. Mazzella, E. Holland, "A New Algorithm to Control DGPS Measurement Errors in Both Base Stations and Navigation Receivers, and Simplify WAAS Error Modeling," Proceedings of ION GPS-95, Institute of Navigation, Alexandria, VA, 1995.

Bishop, G.J., A.J. Mazzella, E.A. Holland, S. Rao, "An Overview of Ionospheric Effects and Mitigation in RF Communications, Navigation and Surveillance," Ionospheric Effects Symposium, 1996

Bishop, G.J., E.J. Weber, A.J. Mazzella, Jr., E.A. Holland, S. Rao, P. Ning, "Simultaneous TEC Decreases and Scintillation Observed on GPS Signals Traversing Equatorial Plasma Depletions," Ionospheric Effects Symposium, Alexandria, VA, 1996.

Lunt, N., L. Kersley, G. Bishop, A. Mazzella, "Protonospheric Electron Contents From GPS/NNSS Observations," International Beacon Satellite Symposium, 1997.

Bishop, G.J., D.S. Coco, N. Lunt, C. Coker, A.J. Mazzella, L. Kersley, "Application of SCORE to Extract Protonospheric Electron Content from GPS/NNSS Observations," Institute of Navigation GPS-97, 1997.

Valladares, C.E., R. Sheehan, A. Mazzella, G. Bishop, S. Basu, K. Groves, "Observations of Equatorial Plasma Irregularities using GPS Receivers and UHF Spaced Antennas," presentation at IAGA, Upsala, Sweden, Feb 1997.

Bishop, G., A. Mazzella, S. Rao, A. Batchelor, P. Fleming, N. Lunt, L. Kersley, "Validations of the SCORE Process," Institute of Navigation NTM-97, Mar 1997.

Doherty, P., D. Anderson, G. Bishop, A. Mazzella, "Ionospheric Effects on Single Frequency GPS Positioning (poster)," Space Weather Effects Workshop, Oct 1997.

Mazzella, A., E. Fremouw, J. Secan, C. Curtis, G. Bishop, "An Algorithm for Simulating Scintillation (poster)," Space Weather Effects Workshop, Oct 1997.

Bishop, G.J., D. S. Coco, N. Lunt, C. Coker, A. J. Mazzella, L. Kersley, "New Methods for Monitoring the Protonosphere (poster)," Space Weather Effects Workshop, Oct 1997.

References

Andreasen, C. C., E. J. Fremouw, E. Holland, A. Mazzella, G.-S. Rao, and J. A. Secan, Observation, analysis and modeling of ionospheric Total Electron Content (TEC) and scintillation effects," *Report PL–TR–96–2227,* Phillips Laboratory, Hanscom AFB, MA, 1996. ADA325078

Daniell, Jr., R. E., L. D. Brown, D. N. Anderson, M. W. Fox, P. H. Doherty, D. T. Decker, J. J. Sojka, and R. W. Schunk, Parameterized ionospheric model: A global ionospheric parameterization based on first-principles models, Radio Sci., 30, 1499-1510, 1995.

Fremouw, E. J., C. C. Andreasen, and J. A. Secan, "Investigations of ionospheric total electron content and scintillation effects on transionospheric radiowave propagation," *NWRA–CR–94–P223,* Northwest Research Associates, Inc., Bellevue, WA, 1994.

Fremouw, E. J., R. C. Livingston, and D. A. Miller, "On the statistics of scintillating signals," *J. Atmospheric and Terrestrial Phys. 42*, 717-731, 1980.

Gallagher, D. L., P. D. Craven, and R. H. Comfort, An empirical model of the earth's plasmasphere, Adv. Space Res., 8, 15-24, 1988.

Secan, J. A., M. P. Baldwin, and L. A. Reinleitner, Real-Time Scintillation Analysis System, Volume 1: Technical Description, *Report NWRA–CR–89–R049,* Northwest Research Associates, Inc., Bellevue, WA, 1990.

Secan, J. A., C. C. Andreasen, E. J. Fremouw, E. A. Holland, and A. J. Mazzella, Jr., Analysis of Ionospheric Monitoring System (IMS) Total Electron Content (TEC) data and equatorial phase-scintillation data, *Report PL–TR–95–2116,* Phillips Laboratory, Hanscom AFB, MA, 1995. ADA306451

Sultan, P., Satellite signatures of the global occurrence morphology of equatorial spread F, *1996 Ionospheric Effects Symposium,* J. Goodman, ed., Springfield, VA, 287-292, 1996, NTIS PB97-10010.

Appendix

Consultant Support to the High Frequency Active Auroral Research Program

John E. Rasmussen
and
Arnold L. Snyder, Jr.

Introduction: Consultant support to the High Frequency Active Auroral Research Program (HAARP) began in July 1996 for Mr. Rasmussen and in August 1996 for Dr. Snyder and has continued to date. The consultants combine experience and understanding of the Department of Defense acquisition process, facility planning, impacts on ionospheric dependent and affected systems, auroral and ionospheric physics, auroral latitude ionospheric measurements and diagnostic instrumentation for upper atmospheric observations. This combination of skills has proven beneficial to HAARP in program planning, management and coordination with prime and subcontractors and various elements of the scientific community. A summary follows for each of the major consultant activities undertaken in support of HAARP.

Overall Diagnostic Instrumentation Coordination: The HAARP program has acquired an array of over twenty state-of-the-art instruments to provide auroral latitude data on a continuous basis and to observe and interpret heater induced phenomena. Support was provided in representing these instruments in program planning, in deployment, integration, display, data archiving, data dissemination and research campaign planning.

Incoherent Scatter Radar Design Panel: A memorandum of agreement existed between the High Frequency Active Auroral Research Program and the Atmospheric Sciences Division of the National Science Foundation to explore the feasibility of developing a common incoherent scatter radar that would satisfy the needs of both organizations. The purpose of the subject panel was to determine if a common design would meet the requirements established previously for the two radars. The Panel was organized, the report drafted, coordinated, finalized, and provided limited distribution. The Panel was chaired by Professor William E. Gordon. The Panel results revealed that a common "core" radar would satisfy the requirements of both organizations but that an adjunct receive array was required to meet the resolution requirements for HAARP F-region studies.

HAARP Site Infrastructure Planning and Development: Support was provided that resulted in an upgrade to the site infrastructure for support of diagnostic instrumentation. This included the coordination of the site layout needed for ionosonde transmit and receive antennas, repositioning of the optical measurement shelter, improved use of the existing temporary trailer-based operations center and the definition of approaches for the development of a permanent Operations Center in the HAARP site Power Plant Building. The improvement and further development of the site infrastructure provides a permanence to the diagnostic instrumentation and enhances principal investigator enthusiasm for broadening the type and number of instruments operating continuously at the HAARP site. The first attempt to define an Operations Center design resulted in an

architectural cost estimate that exceeded program budgetary estimates. Using the acquisition approach of cost as an independent variable (CAIV) a second design effort was initiated and coordinated with the prime contractor and the Alaskan architectural design firm. An operations center user survey was developed and administered. The survey resulted in a definition and prioritization of the functions and approximate room sizes that are needed for a permanent HAARP Operations Center.

University Of Alaska Fairbanks Coordination: The Geophysical Institute of the University of Alaska Fairbanks (GI/UAF) offers a unique resource of scientific talent and data relevant to HAARP. Support was provided to coordinate University activities with HAARP to acquire ELF and geomagnetic data, associated scientific studies and educational outreach programs. The existing contract for GI/UAF support to HAARP concludes in December 1998 and the coordination has included development of a follow-on, multi-year University HAARP-related research plan. In addition, a shorter-term requirement was established to conduct site-surveys for ULF/ELF/VLF receiver measurements needed to characterize the ionospheric source region of these HAARP generated waves. The short-term work requirement for University work was coordinated with the Office of Naval Research (ONR) and undertaken under an ONR grant. Agreement was reached on a common file format for the exchange of diagnostic data between the University Poker Flat Research Range and HAARP.

HAARP Program Planning: Given the nature of Congressional Initiative Programs, outyear planning is a continuing challenge as the government may not obligate or commit funds to undertake activities that require funding from more than a single year appropriation. This requires tailoring of activities for contractual actions to be consistent with current year Congressional appropriations and authorizations. In addition, outyear planning is updated to structure work consistent with expected Congressional funding levels. This planning was coordinated with the HAARP prime contractor to define realistic work packages and update associated cost estimates. Transmitter/Antenna Interface: During the Fall of 1996 and the Winter of 1996-97, prime contractor tests revealed system resonances that resulted in significant antenna tower currents and radio frequency energy dissipation in the antenna tower power suppressers. Both of these situations limited the frequency and/or the beam scanning operations of the HAARP high frequency transmitters. Similar conditions existed in 1994 and led to a redesign of the transmitter antenna interface. Given the long-term existence of this situation, it was recommended that an expert government review team be formed to evaluate the situation and recommend a corrective approach. The government review team was formed, the situation evaluated and eventual concurrence reached with the prime contractor for a corrective design. This design change is being implemented and will be available in the Fall of 1998 for full scale tests.

Diagnostic Instrumentation Planning and Implementation: Efforts were made to continue the upgrade of the Gakona, AK HAARP site diagnostic instrumentation, including installation, operation, and data handling and processing. The winter 1997 HAARP science campaign clearly established the need for an ionosonde for frequency management of the HAARP transmitter. With Dr. Terry Bullett (AFRL), the antenna materials list was established and suppliers located for various transmit and receive antenna components. The ionosonde antenna installation is planned for the summer of 1998 followed by routine operation and data collection. Diagnostic instrument data

monitoring via the Naval Research Laboratory HAARP Web Page has revealed at times the need for instrument repair and/or the need for additional processing to make the data more meaningful and useful. Following identification of the need, the repairs and/or processing needs have been coordinated with the principal investigators responsible for the instruments.

RF Ionospheric Interactions Workshop: We coordinated the NSF/DoD sponsored workshop, held annually in Santa Fe, New Mexico, which has attracted over one hundred scientists to a program of tutorials, invited talks, presentations on facility status, poster presentations and research campaign planning. This activity has included agenda development, facility arrangements, Steering Committee coordination, registration, and the publication of workshop proceedings.

Public and Educational Outreach: We supported the planning and participated in the yearly Gakona, AK HAARP Open Houses and visits by senior officials of the Department of Defense (DoD). Worked with the University of Alaska, Prince William Sound Community College and the Glennallen Schools in developing cooperative programs including a one day College credit course, public lectures on HAARP and the ionosphere and public school curriculum development. These events are planned and conducted to promote program awareness, understanding, and the potential for innovative research for DoD applications.